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EEG and neuronavigated single-pulse TMS in the study of the observation/execution matching system: Are both techniques measuring the same process?

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ABSTRACT

It is now well established that the human brain is endowed with a system that matches the observation of actions with their execution. At the motor cortex level, EEG mu rhythm modulation (8–12 Hz) and TMS-induced motor evoked potentials (MEPs) are two techniques commonly used to assess brain activity during action observation. While both techniques have reliably demonstrated similarities in the pattern of activity induced by action production and action observation, the relationship they bear with each other remains elusive. In the present study, we combined ongoing EEG recordings and single-pulse TMS during the execution, imagination and observation of simple hand actions. Relationship between MEPs and EEG frequency bands at the individual level was investigated. Our results replicate those obtained independently with both techniques: a significant increase in MEP amplitude and a significant attenuation of the mu rhythm during action observation, imagination and execution compared to rest. Surprisingly, we found no significant correlation between MEP amplitude and mu rhythm modulation. However, modulation in the low to midrange beta (12–18 Hz) was related to MEP size during the rest and execution conditions. These results suggest that although mu rhythm and TMS-induced MEPs are sensitive to motor resonance mechanisms, they may reflect different processes taking place within the observation/execution matching system.

1. Introduction

In the last decade, the primary motor cortex (M1) has been associated with a number of cognitive processes that go well beyond simple motor production (Carpenter et al., 1999; Molnar-Szakacs et al., 2005; Richter et al., 2000). Indeed, it now seems that what was once thought to be a unimodal motor production area is also recruited by higher order cognitive processes where no motor output is required. One of the newly discovered properties of M1 that has garnered the most attention is its ability to respond to the passive observation of motor acts as though the observer was actually performing the action (Tkach et al., 2007). Using a variety of brain imaging techniques, studies have pointed out striking functional similarities between the patterns of M1 activity seen during the execution and passive observation of motor acts (Fadiga et al., 2005). In both instances, common regions are not only activated but the mapping is surprisingly refined, such that enhanced activity seen in M1 during action observation is specific to the muscles recruited in the observed action (Fadiga et al., 1995; Strafella and Paus, 2000). Moreover, there is a close temporal coupling between the seen action and the muscle-specific increase in cortical excitability (Gangitano et al., 2001). These findings, combined with the discovery of cells in the macaque brain that respond to the execution and observation of actions (mirror neurons; Rizzolatti et al., 1996), have led to the formulation of the motor resonance hypothesis (Rizzolatti and Craighero, 2004). While the exact role of this system is still a matter of debate, it is thought to contribute to action understanding and imitation (Rizzolatti and Craighero, 2004).

When applied over M1, single-pulse transcranial magnetic stimulation (TMS) induces a corticospinal volley that produces an involuntary muscle twitch in the corresponding body part of the motor homunculus that can be reliably measured with

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electromyography (the motor evoked potential; MEP). TMS-induced MEPs can be used to quantify the motor output resulting from the depolarization of cortical neurons through TMS stimulation. MEP amplitude varies as a function of TMS intensity, but it is also sensitive to factors that influence corticospinal excitability (Pascual-Leone et al., 1998). When intensity is held constant across experimental conditions, the variation of amplitude observed in MEPs is thought to reflect heightened or diminished M1 excitability. Using this technique, Fadiga et al. (1995) provided the first evidence of an observation/execution matching mechanism in human M1. They showed that MEP amplitudes recorded from the hand significantly increased during conditions in which participants passively observed hand movements. This motor facilitation during action observation has since been replicated in numerous studies (Aziz-Zadeh et al., 2002; Maeda et al., 2002; Strafella and Paus, 2000; Urgesi et al., 2006). It also seems that observation of action is not necessary to elicit motor facilitation, as mere imagination of a movement can be sufficient to increase corticospinal excitability. Indeed, studies investigating motor visualization (or motor imagery), in which the individual is asked to rehearse within working memory a dynamic movement, also showed increased MEP size compared to baseline conditions (Izumi et al., 1995; Mercier et al., 2008; Stinear et al., 2006). These data strongly suggest that different motor embodiments, externally as well as internally generated, are mapped onto the cortical representation of an onlooker's motor system.

Another indicator of sensorimotor activity that is increasingly used in the study of motor resonance mechanisms is the EEG mu rhythm (Bernier et al., 2007; Lepage and Théoret, 2006; Muthukumaraswamy et al., 2004; Oberman et al., 2005a,b; Stroganova et al., 2007). Located in the alpha band (8–12 Hz) and of maximal amplitude over central sites (C3–C4) at rest, the mu rhythm is strongly suppressed during the performance of controlateral motor acts (Pineda, 2005). Desynchronization of the mu rhythm over central sites during motor performance is believed to reflect M1 recruitment through thalamocortical input. The hypothesis that decreased mu rhythm power is related to cortical activation is supported by simultaneous EEG and fMRI studies showing a negative relationship between EEG alpha rhythms power and the fMRI BOLD signal (Laufs et al., 2006). Recent studies have shown that observation (Muthukumaraswamy et al., 2004) and imagination (Pfurtscheller and Neuper, 1997) of motor actions are sufficient to attenuate rolandic mu rhythm amplitude. In the absence of overt movement, diminution of this sensorimotor rhythm is thought to be the product of fronto-parietal networks that map a perceived action onto the motor system, which ends up modulating activity within motor regions (Pineda, 2005). The pattern of M1 activity during both the execution and the observation of motor acts is congruent with the hypothesis that mu rhythm modulation reflects the activity of motor resonance mechanisms in the human brain. Moreover, much like single-pulse TMS studies have shown, it seems that mu rhythm modulation within sensorimotor areas is specific to the cortical region corresponding to the body part recruited in the observed or imagined movement (Pfurtscheller et al., 2006).

Modulation of oscillatory brain activity has been linked to changes in cortical excitability (Pfurtscheller, 2001) and although increased amplitude of the TMS-induced MEP and blocking of the mu rhtyhm during action observation/execution/imagination has been well documented, the link between both measures has not been directly investigated. In the visual system, individuals who display lower alpha band power at rest over posterior areas also show higher visual cortical excitability as indexed by phosphene threshold (Romei et al., 2008). Furthermore, at a trial-by-trial level, low prestimulus alpha band power has been associated with increased visual cortex excitability (Romei et al., 2007). In motor cortex, however, the link between oscillatory fluctuations and corticospinal excitability is less clear. In a recent study, Mitchell et al. (2007) reported only weak correlation between EEG activity and size of the TMS-induced MEP during a precision grip. In the present study, we combined continuous EEG recordings and single-pulse TMS to investigate motor resonance mechanisms. Both measures were acquired during the performance, the imagination and the observation of actions to determine whether both methods, which are widely used in the study of motor resonance, would correlate at the individual level. One crucial prerequisite to allow the establishment of a relationship between TMS-induced MEPs and EEG oscillations is the stability of measurements. With this in mind, we used a neuronavigating system to ensure stable coil positioning throughout the experimental procedure.

2. Materials and methods

2.1. Participants

Data were obtained from 16 right-handed volunteers (8 females, 8 males, 20–28 years old; mean age = 24.75 years, S.D. = 2.86) with no history of neurological disorders. All subjects reported being in good health, having normal vision and not being on psychoactive medication. Written informed consent was obtained and the experimental protocol was approved by the *Comité d'éthique de la recherche de la Faculté des arts et des sciences* of the Université de Montréal.

2.2. EEG

The experimental procedure took place in a Faraday room. EEG was acquired from four 8 mm carbon electrodes (Easycap, Herrsching-Breitbrunn, Germany) located on C3–Cz–C4 and Oz sites of the International 10–20 system of electrode placement. While only electrodes over central sites (C3, Cz, C4) are indicative of sensorimotor cortex activity, the Oz location over occipital cortex was used as a control site. EEG was recorded using Scan 4.2 Acquisition Software (Neuroscan, Charlotte, USA) running on a PC computer and amplified using a Neuroscan NuAmps system (Neuroscan, Charlotte, USA). EEG was digitized at 1000 Hz, with a bandpass filter of 0.1–100 Hz. All electrode impedances were inferior to 5 kΩ. A grounding electrode was placed on the forehead of the participant with the reference averaged from electrodes located on the left and right ears.

2.3. TMS

TMS was delivered with a Medtronic Magpro 100× TMS device (Medtronics, Minneapolis, USA) with a 80-mm-diameter figure-of-eight coil. To minimize electromechanical noise on the EEG recordings, a customized shielding device made of 5 mm-thick rubber-foam was positioned between the coil and the subject's head during stimulation sessions. The current waveform was biphasic and the coil was angled 45° from the midline with the handle pointing backward. Pulses were delivered over the left primary motor cortex corresponding to the hand region. MEPs were recorded from electrodes placed over the contralateral first dorsal interosseus (FDI) muscle and a circular ground electrode was placed over the participants' wrist. The electromyographic signal was amplified using a Powerlab 4/30 system (ADInstruments, Colorado Springs, USA), filtered with a band pass 20–1000 Hz and digitized at a sampling rate of 4 kHz. MEPs were recorded using Scope v4.0 software (ADInstruments, Colorado Springs, USA) and stored offline for analysis. Prior to the experimental procedure, the stimulation site